

FULL ENVELOPE RECONFIGURABLE CONTROL DESIGN FOR THE X-33 VEHICLE

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Abstract

In the event of a control surface failure, the purpose of a reconfigurable control system is to redistribute the control effort among the remaining working surfaces such that satisfactory stability and performance are retained. An Off-line Nonlinear General Constrained Optimization approach was used for the reconfigurable X-33 control design method. Three examples failures are shown using a high fidelity 6 DOF simulation (case 1 : ascent with a left body flap jammed at 25 deg. ; case 2 : entry with a right inboard elevon jam at 25 deg. and case 3 : landing (TAEM) with a left rudder jam at -30 deg.) Failure comparisons between responses with the nominal controller and reconfigurable controllers show the benefits of reconfiguration. Single jam aerosurface failures were considered, and failure detection and identification is considered accomplished in the actuator controller. The X-33 flight control system will incorporate reconfigurable flight control in the baseline system.

X-33 Aircraft Description

The X-33 is a subscale, suborbital demonstrator for the proposed Lockheed Martin VentureStar® single-stage-to-orbit commercial launch vehicle. As shown in Figure 1, the X-33 has four sets of aerosurfaces: rudders, body flaps, and inboard and outboard elevons. The X-33 also relies on engine thrust vectoring and reaction control system thrusters for vehicle control.

The X-33 will be the first aircraft to use electromechanical actuators (EMA's) to power all the primary flight control surfaces. All of the aerosurfaces on the vehicle will use one or more of a particular Allied Signal two-channel EMA. Control reconfiguration could occur within 120-160 ms., including failure

detection and identification. Our analysis has shown a few (very unlikely) single-failure modes for the actuators, failures that would most likely result in jam of the associated aerosurface.

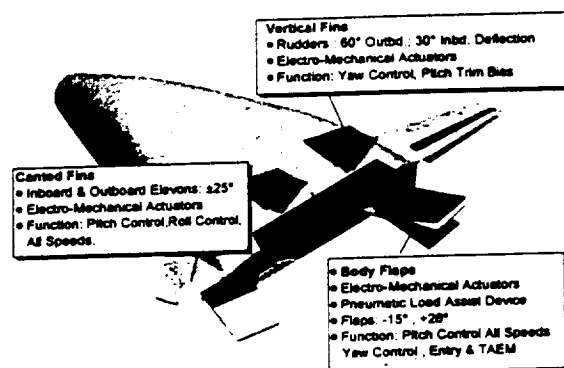


Figure 1: X-33 Vehicle and Aerosurfaces

The X-33 vehicle is controlled through a triplex fly-by-wire flight control system built by Allied Signal and operating at 50 samples per second (20 msec.).

Reconfiguration Scope

The baseline flight control system for the X-33 contains control reconfiguration because the vehicle has low control redundancy compared to other aircraft. The primary motivation for pursuing reconfigurable control for this vehicle was in anticipation of greater control redundancy as well as the high value of reconfiguration with VentureStar®. In designing the reconfigurable control jam failures were assumed in each of the eight aerosurfaces. Engine thrust vectoring and reaction control system thrusters, although part of the primary flight control system, are not part of the reconfigurable control.

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Reconfigurable Control Design

The four reconfigurable control design methods investigated for the X-33 vehicle were the Redistributed Pseudo-Inverse, General Constrained Optimization, Automated Failure-Dependent Gain Schedule, and the Off-line Nonlinear General Constrained Optimization approach¹. The Off-line Nonlinear General Constrained Optimization approach was chosen for implementation on the X-33. A discussion of the Off-line Nonlinear General Constrained Optimization approach and preliminary results of this approach implemented in a six degree of freedom simulation can be seen below.

Off-Line Nonlinear Constrained Optimization (ONCO)

With prior knowledge of the failure assumed, it was decided that a simple table look-up of the failure to determine the controller changes would meet the requirements of reconfiguration and was an approach that could be easily implemented. A table look-up of the mixer gains would have the added advantage of being easily tested in the validation and verification process required before the first vehicle flight. Therefore, it was decided that an off-line method would have the best chance of success for the X-33 flight program, and the Off-Line Nonlinear Constrained Optimization (ONCO) approach was chosen.

Figure 2 shows the X-33 control block diagram for the entry phase of flight. For this type of reconfiguration (ONCO), the mixer is modified. The nominal entry mixer is shown in Figure 3, and the reconfigurable mixer is shown in Figure 4. The reconfigurable control mixer has more interconnect gains. The roll command is sent to all the remaining actuators through a set of gains, whereas, with the nominal mixer, the roll command is sent only to the elevons. The procedure of increasing interconnects was duplicated for the pitch and yaw commands. Once a failure has occurred, the nominal mixer is disabled, and the reconfigurable mixer is brought on-line within 280 msec. of the failure.

The mixer gains were determined beforehand (off-line), using a Sequential Quadratic Programming (SQP) method. This quasi-Newton method is solved for each iteration of the Quadratic Programming (QP) problem and updates an estimate of the Hessian of the Lagrangian using the BFGS formula². The constrained non-linear optimization is shown in equation (1):

$$\text{Min}_X f(X) \text{ subject to } G(X) \leq 0$$

(1)

If $f(X)$ is twice differentiable, then there exists a matrix of second partial derivatives or Hessian matrix

$$G(X) = \nabla^2 f(X)$$

where G is a positive semi-definite matrix and $H \approx G^{-1}$. Note that $(G^{(k)})^{-1}$ is approximated by a symmetric positive definite matrix $H^{(k)}$. The expression shown in

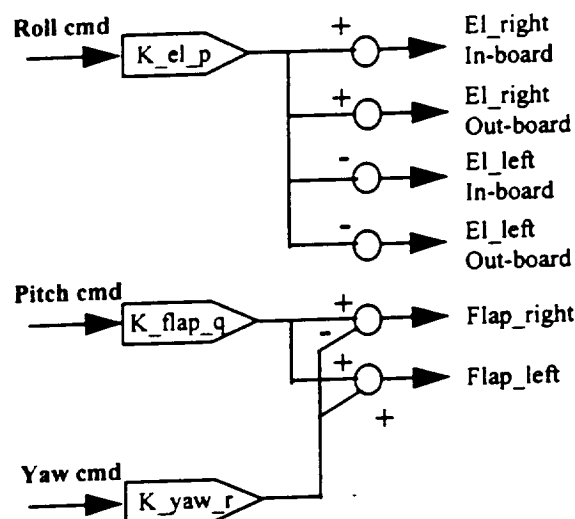


Figure 3: Nominal Entry Control Mixer

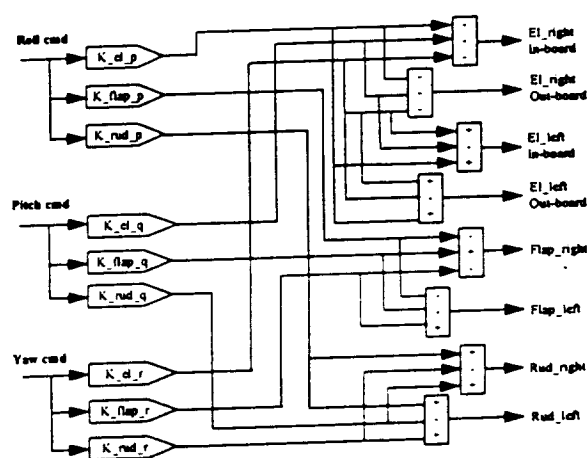


Figure 4: Reconfigurable Control Entry Control Mixer

equation (2) below is sometimes called the quasi-Newton condition^{3,4}.

$$H^{(k+1)} \gamma^{(k)} = \delta^{(k)} \quad (2)$$

An important relationship was suggested by Broyden, Fletcher, Goldfarb and Shanno and is known as the BFGS formula (equation (3))^{4,5}.

$$H_{BFGS}^{(k+1)} = H + \left(1 + \frac{\gamma^T H \gamma}{\delta^T \gamma}\right) \frac{\delta \delta^T}{\delta^T \gamma} - \left(\frac{\delta \gamma^T H + H \gamma \delta^T}{\delta^T \gamma}\right) \quad (3)$$

The ONCO method optimizes a time-domain response. Using equation 3 to constrain the time-domain errors and allowing the gains shown in Figure 4 to be the tunable parameters, a series of closed loop off-line simulations are run. After a simulation run (usually a step command response), the errors between the commanded and the actual response is summed and a new simulation trial is run with a modified gain set. The modified gain set is the result of equation 3 to find a constrained optimal reduction in the summed error. The simulation commands were a combination of roll and pitch steps in which the size of the roll command was 20 deg. and the size of the pitch command was 2 deg. The size of the roll and pitch commands were found to be large enough to stress the algorithm optimization. It was found it necessary to execute a pitch and roll command simultaneously to couple the dynamics.

Optimization based on the BFGS formula was found to work satisfactorily for the X-33 reconfigurable control law design. The limitations of the SQP method are that the function to be minimized and the constraints must be continuous, and the method may only give local solutions. The controls tool package used for the reconfiguration development was the MathWorks Nonlinear Control Design Blockset⁶.

The initial gains were implemented in a 6-DOF simulation. It was determined that the gains were too large due to differences between our linear models and the nonlinear simulation. Gain reduction was then required for adequate 6-DOF results.

Results and Discussion using a Nonlinear Simulation (6 DOF)

Three flight phases (ascent, entry and TAEM) were explored using the nominal controller and the reconfigurable controller with three different jammed surfaces. All three cases had a reconfiguration switching time of 280 msec after the failed actuator was declared off-line.

Time history results for the entire X-33 entry flight phase were obtained with a 6-degree-of-freedom nonlinear simulation. The reconfigurable mixer gains were generated for each failed control surface at several points along the trajectory. These gains were then used to build a two-dimensional gain schedule as a function of Mach number and failed surface deflection. The resulting schedules were implemented in the X-33 6-DOF simulation.

Upon initial testing of the reconfigured mixer gains, some rate limiting and position saturation was observed. After a few simple gain reduction simulation trials, very good results were obtained.

Ascent Phase

The ascent controller is a Euler command tracking system.⁶ During the ascent phase, attitude control is provided by rocket engine thrust vector control (TVC) and the aerosurfaces. When a control surface has jammed all the remaining operational control surfaces in conjunction with the TVC will be used for control.

Figure 5a shows the response of the vehicle in the case of the left body flap jammed at 25 degrees, 20 seconds after lift-off for the nominal and reconfigurable control systems. The time history shows the nominal controller with the failed surface (dashed line) held theta (pitch attitude) error to within 5 degrees in the longitudinal axis. With the reconfigurable controller (solid line), theta error was reduced to 2 degrees. Figure 5b shows the lateral axis response to the left body flap failure. Phi (bank angle) was controlled to within 8 degrees with the nominal controller and to within 3 degrees with the reconfigurable control system.

During the ascent phase of flight, the loads on the aircraft must be kept to a minimum so that the structural integrity is not jeopardized. Two of the design parameters used for structural load minimization are the terms ($q\alpha = Qbar * \alpha$ and $q\beta = Qbar * \beta$). For the directional axis, if the sideslip angle (β) is close to zero then the side loads ($q\beta$) will not be a structural problem. Figure 5c shows a time history of $q\alpha$ and $q\beta$ for the failed ascent case. The results show that a reduction in aerodynamic loads will occur if reconfigurable controls are used.

The body flaps are the most effective aero surface on the X-33 and conversely are the most difficult to reconfigure in the event of a failure. Overall ascent results show that the nominal controller can handle any aerosurface failure. The reconfigurable controller, however, holds the vehicle closer to the desired flight trajectory.

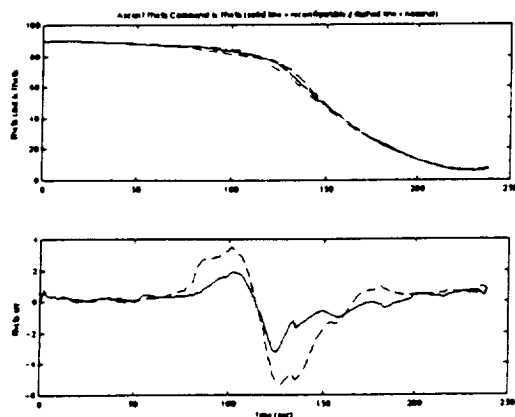


Figure 5a: Ascent Pitch Attitude Time Response.
Nominal Controller = Dashed Line, Reconfigurable
Controller = Solid Line

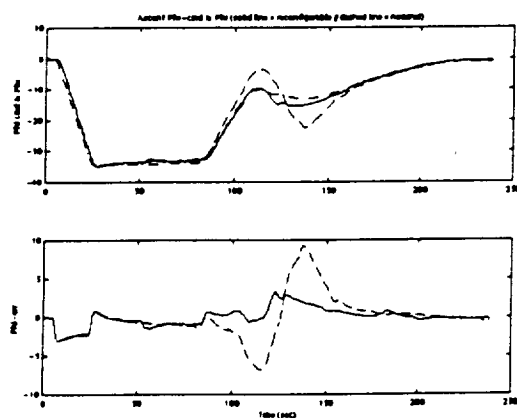


Figure 5b: Ascent Roll Attitude Time Response.
Nominal Controller = Dashed Line, Reconfigurable
Controller = Solid Line

Entry Phase

The entry controller is a alpha command tracking system for the longitudinal axis and a bank command system for the lateral axis.⁷ The entry control system has aerosurfaces and eight Reaction Control System jets (thrust from one RCS jet is 500 lb.) for control effectors.

Approximately 10 seconds into the entry phase, the right inboard elevon is failed to a positive 25 deg. as shown in Figure 6a. The nominal mixer maintains control of the vehicle for about 70 seconds (nominal controller is shown with the dashed line), when it departs in the lateral-directional axis (Figure 6b). A few seconds later, the vehicle also departs longitudinally. For the

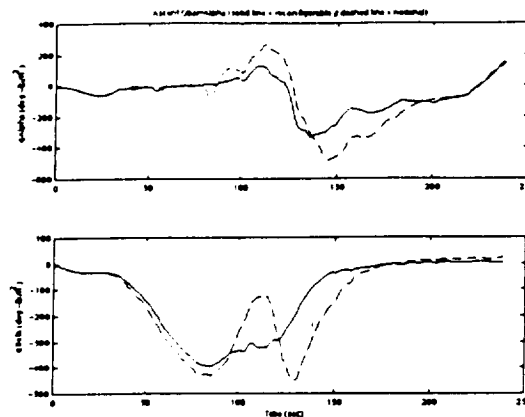


Figure 5c: Ascent Aero Load Indicator Time Response.
Nominal Controller = Dashed Line,
Reconfigurable Controller = Solid Line

same failure, the reconfigured mixer is able to follow the commands for the entire entry flight phase.

The control effectors (surface positions) from the two simulated flights are cross-plotted in Figure 6c. When the right inboard elevon jammed at +25 deg (down) the left inboard nominal controller (dashed line) did not compensate fully for this reaction, and as a result, the vehicle departed. However, as also shown in Figure 6c the reconfigurable controller (solid line) compensated for the right inboard elevon jam by commanding the left inboard elevon to +23 degrees.

The reconfigurable controller uses elevons, flaps, and rudders to control the vehicle and achieve the desired tracking commands from guidance. As can be seen from Figure 6, reconfigurable controls allows the

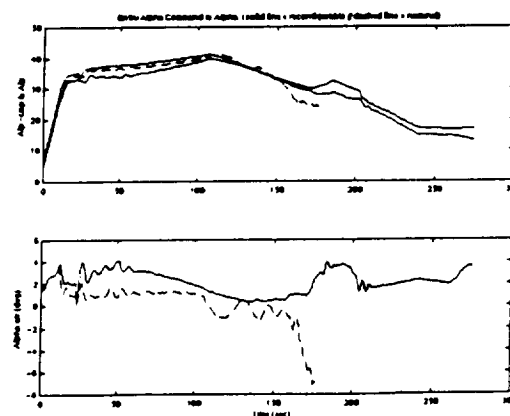


Figure 6a: Entry Angle of Attack Time Response.
Nominal Controller = Dashed Line, Reconfigurable
Controller = Solid Line

vehicle to continue on the desired trajectory to a safe entry conclusion (Mach 3)

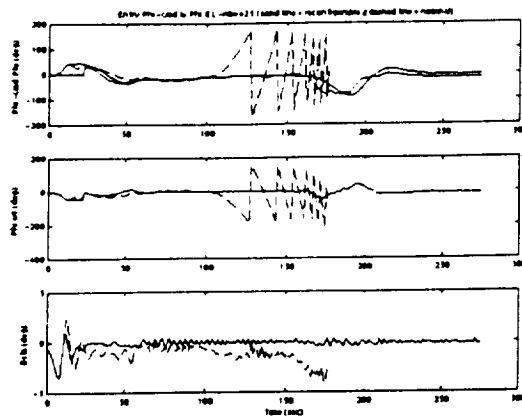


Figure 6b: Entry Lateral Directional Time Response. Nominal Controller = Dashed Line, Reconfigurable Controller = Solid Line

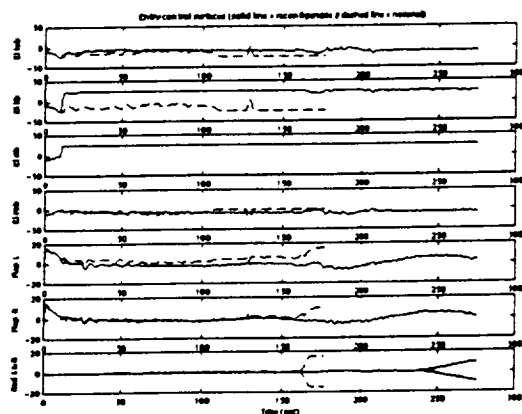


Figure 6c: Entry Control Surface Time Response. Nominal Controller = Dashed Line, Reconfigurable Controller = Solid Line

TAEM Phase

The TAEM (Terminal Area Energy Management: from Mach 3 down to landing) controller is a Nz command system for the longitudinal axis and a bank command system (Phi) for the lateral axis. The TAEM control system has aerosurfaces and RCS jets down to Mach 2.

Approximately 20 seconds in the TAEM flight phase, the left rudder jammed at -30 degrees (trailing edge right). The results are shown in Figure 7a, b and c.

The nominal TAEM controller Nz and alpha time histories are shown in Figure 7a (dashed line) and departs by 40 seconds. The lateral axis results are shown in Figure 7b. The nominal controller departs in beta by 50 seconds. Figure 7c shows the longitudinal and lateral ground track. The nominal controller can not execute the turn (also known as the HAC (heading alignment cone)), whereas the nominal controller continues down to a survivable landing. The reconfigurable controller lands with a sink rate of -7 ft/sec (Figure 7c / solid line).

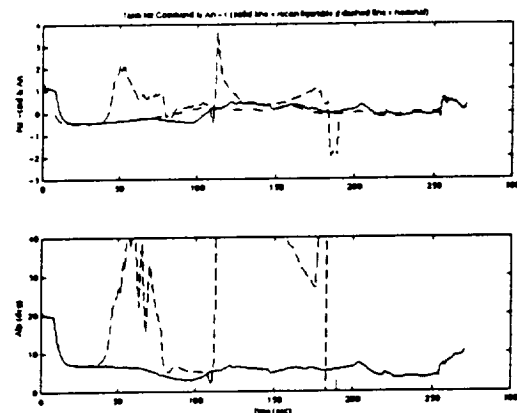


Figure 7a: TAEM Nz and Angle of Attack Time Response. Nominal Controller = Dashed Line, Reconfigurable Controller = Solid Line

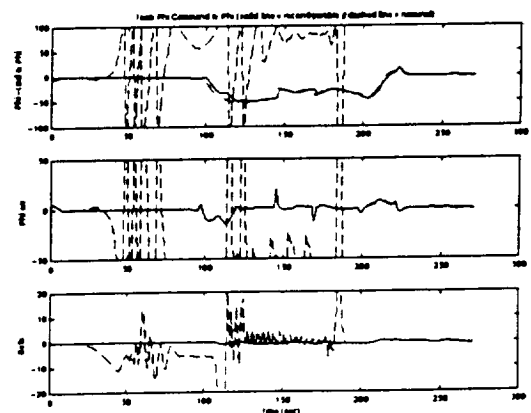


Figure 7b: TAEM Lateral Directional Time Response. Nominal Controller = Dashed Line, Reconfigurable Controller = Solid Line

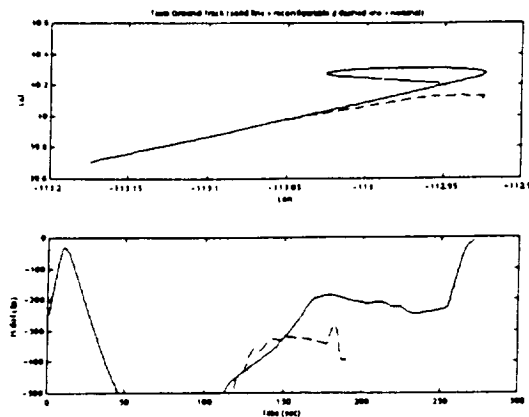


Figure 7c: TAEM Landing Criteria. Nominal Controller = Dashed Line, Reconfigurable Controller = Solid Line

Concluding Remarks and Discussion

A reconfigurable control system has been designed and tested on a full nonlinear simulation for the X-33 vehicle. The reconfiguration design scope was limited to control surface failures. The methodology chosen for the reconfiguration was a Off-line Nonlinear Constrained Optimization approach. With this design philosophy, a known failure was assumed, and a pre-specified mixer gain controller was used. The reconfigurable controller is chosen based on a table look-up of surface jammed and the jam position. The reconfigurable controller gains are updated at 10 Hz with the controller operating at 50 Hz. The time to reconfigure after a failure was determined to be between 240 to 360 msec., including failure detection and identification.

Although only three failure examples were presented in the paper (a left body flap ascent / inboard elevon entry / and a rudder landing failure), reconfigurable control was designed for the entire X-33 flight envelope. Our overall design effort showed that certain control failures were much easier to accommodate than others, as shown in Table 1 below.

Table 1: X-33 Surface Failure Accommodation		
Failed Surface	Reconfiguration Difficulty	Region of Successful Reconfiguration
Body Flap	Very Difficult	Limited surface positions 0. < Mach < 2.5

		$-3 < \delta_{\text{flap}} < +5$
Elevons	Moderately Difficult	All surface positions. All Mach numbers: $-30 < \delta_{\text{elevon}} < +30$
Rudder	Easy for entry Difficulty landing	All surface positions. All Mach numbers $-30 < \delta_{\text{rudder}} < +30$

Based on the results of the fully nonlinear simulator work, the project has determined that the control reconfiguration system will be included on board the X-33 vehicle. This will be the first non-controls-research vehicle to incorporate reconfigurable flight control in the baseline control system.

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